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THE ROLE OF RESPIRATORY HEAT EXCHANGE IN THE PRODUCTION OF EXERCISE-INDUCED ASTHMA

Running title: Respiratory Heat Exchange and Asthma

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ABSTRACT

By having our subjects inhale dry air at various temperatures ranging from subzero to 80 °C in a random fashion, we have tested the hypothesis that it is the total heat flux in the tracheobronchial tree during exercise that determines the degree of post-exertional obstruction that develops in asthma. Our purpose in this was to determine if heat could be transferred from the air to the mucosa so as to offset evaporative losses from the airways. The observed post-exercise responses were then compared to those that we predicted would occur based upon the relationship of respiratory heat exchange and exercise response determined from previous studies in this laboratory employing fully saturated air. The observed responses breathing completely dry air fell as the temperature was increased and exactly matched theoretical predictions over a range of inspired air temperatures from -11 to 37 °C. Above 37 °C the observed response exceeded predictions, indicating that it was not possible to provide sufficient heat per se in the air to offset the vaporization of water. However, when small amounts of water were added to the inspirate at high temperatures, bronchospasm was virtually abolished and the response again closely matched theoretical expectations. We conclude that the magnitude of exercise induced asthma is directly proportional to the thermal load placed upon the airways and that this reaction is quantifiable in terms of respiratory heat exchange.

INTRODUCTION

We have previously shown that when asthmatics breathe subfreezing air during exercise, the bronchospastic response that develops is greatly accentuated when compared with standard room conditions (1). This potentiating effect of cold air is not reflexly mediated, and appears to be due to the penetration of incompletely conditioned air into intrathoracic airways (2). Under these circumstances the temperature of the mucosa is likely to be lowered far below its normal value during inspiration because considerable quantities of both heat and water must be transferred from the surface of the airways to bring the inspired air to body conditions before it reaches the alveoli. These observations suggested that airway cooling was an important initial local stimulus to the development of obstruction. When we explored the relative roles played by convective and evaporative heat losses in producing mucosal cooling, we were able to demonstrate that the magnitude of the airway obstruction was inversely proportional to the water content of the inspirate through temperature ranges of 25 to 37°C (3). Thus, the chief factor that relates to the development of exercise-induced asthma, and the principle cause of mucosal cooling is the vaporization of water. Strong support for this reasoning has recently been obtained from two investigations that have shown a protective effect when asthmatics exercise while breathing air with high humidity (4,5).

These observations have suggested to us that there may be a quantitative relationship between the total heat flux in the tracheobronchial tree during physical exercise and the degree of obstruction that subsequently develops. If this were so, we have reasoned that if we had subjects inhale air above body temperature during exercise, we should be able to offset or minimize the heat lost from the evaporization of water at the mucosal surface by supplying an over abundance of heat that can be transferred from the inspired to the airway lining. The response to a given exercise task, then, should be entirely predictable whether heat exchange is convective or due to vaporization of water. We have tested this hypothesis by relating the post-exercise obstructive response to total respiratory heat flux during a fixed exercise task while subjects breathed air over a range of temperatures and water contents. Our observations form the basis of this report.

Methods

Eight asymptomatic, atopic individuals with reproducible exercise induced asthma extensively documented in our laboratory served as our subjects. There were 6 women and 2 men with a mean age of 23.6 $\pm$ 1.9 (SD) years. None were smokers and all met the American Thoracic Society's definition of asthma (6). All refrained from taking any medication for 12 hours prior to any study day, and none had used glucocorticoids or cromolyn sodium for at least 4 weeks before study. Informed consent was obtained from each subject.

Lung volumes and airway resistance were measured in a constant volume variable pressure plethysmograph (Warren E. Collins Co., Braintree, MA.) that was serially interfaced to an analog recorder (Electronics for Medicine, White Plains, N.Y.) and a minicomputer (Lab 8E, Digital Equipment Corp.,

Maynard, MA.) (7,8). Airway resistance was expressed as a conductance volume ratio termed specific conductance (SGaw) (9). Five measurements of each variable were routinely obtained and the mean computed. These data were considered acceptable if their coefficients of variation were 5% or less. Spirometry was performed in triplicate using a waterless spirometer (Electro Med. Model 780, Seale Cardio-Pulmonary, G.D. Seale and Co., Houston, Texas). One second forced expiratory volumes (FEV_1) were computed by standard techniques. The subject's best effort as defined by the curve with the largest vital capacity and FEV_1 was used for analysis.

The temperature and water content of the inspired air was controlled by having the subjects breathe through a heat exchanger and bubble humidifier as previously described (3). This instrument complex was capable of producing temperatures between -15°C and 120°C with relative humidities (RH) varying from zero to 100%. The temperature of the inspired air was continuously recorded in all experiments by a thermocouple situated in the airstream within the exchanger and located 10 cm upstream from the mouth. Expired air temperature was also measured with a second thermocouple that protruded through the mouthpiece 5 cm into the oral cavity. The thermocouple was shielded so as not to touch any mucosal surface. Expired gas was directed away from the exchanger through a one-way valve into a tissot spirometer so that tidal volume and minute ventilation (V_E) could be recorded. Heart rate was monitored continuously. The water content of the air supplied to the subjects was verified by drawing a known volume of air through glass drying tubes containing anhydrous calcium sulfate (W. A. Hammond Drierite Co., Xenia, Ohio) as previously described (3). Compressed air served as the source of dry air.

Our studies were performed on 3 non-consecutive days. On the first two days the subjects performed three bouts of exhausting leg work on a cycle ergometer while breathing dry air at -10, 25, 37, 50, 60 and 80°C in a random fashion through the exchanger. On the third day, only 2 exercise periods were undertaken during which dry air at 50°C was randomized with air at 50°C containing approximately 15 mg H_2O/liter. In each of the above experiments the air was inhaled for 4 minutes before, during and for 4 minutes after the exercise period. The work loads, RPM and duration of exercise were held constant for each individual for each study. The mean work load was 881 $\pm$ 203 (SD) KPM, and the mean duration of exercise was 3.24 $\pm$ 0.76 (SD) minutes. Upon completion of a work load, on any study day, the subjects rested for at least one and one-half hours while their pulmonary mechanics returned to preexercise levels before subsequent exercise was undertaken.

Exhausting leg work was used as the provocational stimulus because it was technically easier to have the subjects breathe through the exchanger from a fixed seated position. Previous experience with this form of maximum work has demonstrated its reproducibility and effectiveness (1-3,10,11). Similarly, the duration of work, the interval between studies, and the number of studies performed within a day had all been previously verified (1-3,10-12).

Pulmonary mechanics were measured before and 5 to 10 minutes after cessation of work. Again, prior experiments demonstrated that this time sequence would be appropriate (1-3,10-12).

Respiratory heat exchange (RHE) was computed from the following formula:

$$RHE = \dot{V}_E [HC (T_i - T_e) + HV (WC_i - WC_e)]$$

Where RHE = Respiratory heat exchange in Kcal/min

$\dot{V}_E$ = Minute ventilation in L/min (BTPS)

HC = Heat capacity of air = specific heat · density = .000304 Kcal/L/°C

T_i = Inspired air temperature in °C

T_e = Expired air temperature in °C

HV = Latent heat of vaporization of H_2O = 0.58 Kcal/g

WC_i = Water content of the inspired air in mg H_2O/L air

WC_e = Water content of the expired air in mg H_2O/L air

Since WC_e is difficult to measure physically, we made the assumption that the expired air was fully saturated at T_e. Numeric values for WC_e were then obtained from standard saturation-temperature relationships (13).

The data in this study were analyzed by paired t tests, and one and 2 factor analyses of variance.

Results and Discussion

Table 1 contains individual data for $\dot{V}_E$, T_i and T_e for each of the dry gas studies. The mean minute ventilation ranged between 66.3 and 75.6 L/min, and an analyses of variance indicated that there were no significant differences between studies ($F = 0.72$, $df = 5,47$; PNS). As can be seen, the average inspired air temperatures varied less than a degree from the values chosen for investigation.

The effects of exercise on pulmonary mechanics while breathing dry air at different temperatures are shown in Figures 1 and 2.* Baseline values for each variable for each study were not different, and there was a

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* Individual data are contained in Tables A_1 through A_6. This information is included to facilitate review and is to be deposited with the National Auxiliary Publications Service.

significant post-exercise obstructive response with all gas mixtures given (Figure 1). When these data were analyzed in terms of the absolute change from baseline (Figure 2) the largest responses for each variable occurred with the -10.9°C air. This change was significantly greater by factorial analysis than that observed with any of the warmer air mixtures (e.g., SGaw -10.9°C vs 24.8°C, $P<0.005$; FEV_1 -10.9°C vs. 24.8°C, $P<0.025$; RV -10.9°C vs. 24.8°C, $P<0.005$). These results are similar to those previously reported for cold air (1,2). Comparison of the 25 and 37° responses did not reveal any significant differences. This too is in agreement with previous observations (3,4), and given the relatively small heat capacity of air 0.000304 Kcal/L/°C, an increase in temperature of only 12°C would not be expected to have much effect even if all of the heat were transferred to the mucosa. As can be seen, heating the air above body temperature had no further effect upon the response.

This raises the possibility that either our hypothesis was in error or that the net convective gain occurred mainly in the supraglottic airways with minimal gain of water such that less warm, but still relatively dry air, reached the intrathoracic airways. Indeed, the major subjective response to the superheated air was a severe dryness of the throat and a sensation of parching. Consequently, in an attempt to modify the upper airway convective heat gain and to modulate the evaporative load placed on the intrathoracic airways, we delivered air at 50°C with 15.8 ± 4.1 (SD) mg H_2O/L (Table 2). This water content was chosen because it approximated that found in a room at 26°C with a relative humidity of 60%, a gas mixture that is regularly associated with a brisk post-exercise bronchospastic response. In addition, this combination of temperature and water content

could be safely administered without fear of burning the subjects. The $\dot{V}_E$ in this set of experiments was slightly less (7-8 L/min) than in the earlier 50°C experiment listed in Table 1. However, there were no significant differences in $\dot{V}_E$ between the two inspired air conditions on this day ($t = 0.78$; $df = 7$, pNS). Figure 3 shows the comparative responses of inhaling dry air at 50°C with that of partially saturated air. These data demonstrate that the baseline values for each variable were identical and that although airway obstruction still developed when H_2O was added, the response was significantly less than with dry air at this temperature. Thus, as the thermal burden on the airway was decreased by adding H_2O, so was the response, suggesting that total respiratory heat exchange (RHE) was playing a role.

Since the subjects (with one exception) and the exercise provocation used in this investigation are identical to those of previous studies, and since we have examined the responses observed with fully saturated and completely dry air over a wide range of temperatures, as well as various intermediate combinations of temperatures and humidity, we can explore the relationship of RHE and expected response over all possible climatic conditions. Examination of the relationship between RHE calculated from the formula given earlier and the degree of post-exercise obstruction from previous studies is shown in Figure 4 (1,3). Although this figure displays only change in FEV_1, the same association can be shown for specific conductance, maximum mid-expiratory flow rates, and residual volume. As can be seen there is a linear, highly significant, and positive relationship between the percentage change in FEV_1 and RHE. Given this relationship and our previous results with fully saturated air,

it is possible to predict the response to the various dry gas mixtures in the present study as a function of inspired temperature. This is shown in Figure 5.

The solid circles and lines are the percentage change in FEV_1 found while breathing air at 100% relative humidity in the studies of Strauss, et al., (1,3). These data demonstrate that as the temperature and water content of the inspired air were increased, the post-exercise response decreased until at the point of zero heat exchange (37°C, 44 mg H_2O/L), the response was abolished. The open circles and broken line represent the expected response for dry gas. This curve was obtained by computing RHE using the values for T_i, T_e and $\dot{V}_E$ listed in Table 1, and then relating RHE to FEV_1 through the regression equation in Figure 4. A sample calculation is as follows:

Let T_i = 25°C; T_e = 32°C; Wi = 0 mg H_2O/L; W_e = 34 mg H_2O/L and $\dot{V}_E$ = 70 l/min

Then from equation 1:

1) RHE = 70 L/min [0.000304 Kcal/L/°C(25-32°C) + 0.58 Kcal/g(0-34 mgH_2O/L)]

= 1.53 Kcal/min

from the regression equation in Figure 4:

2) $\%\Delta FEV_1$ = 26.14 (1.53) - 4.16

= 35.8%

The two curves shown in Figure 5 represent the maximal and minimal responses possible at the extremes of humidity over a temperature range from -11 to 110°C for a fixed exercise task. All other combinations of temperature and humidity must, therefore, lie between these outer bounds. For example, at a given T_i, vertical movement up and down the

graph from either extreme is related to the amount of water that would be added or removed to vary the post-exercise FEV_1 at a constant $\dot{V}_E$. Moving horizontally from the 100% relative humidity line toward the 0% line relates to the inspired air temperature that would be required to offset evaporative losses from the mucosa in order to keep the response constant. With dry air, in order to bring about a RHE of zero, and thus abolish the post-exercise response, a T_i of 107°C would be required to provide enough heat in the inspired air to precisely replace mucosal losses from vaporization. At the other extreme of this graph, the 0 and 100% RH curves join. The reason for this is that subfreezing air can hold very little water. For example, the difference between the water content in fully saturated and dry air at -10°C is only 2.4 mg (13). Consequently, this factor does not have much of an influence upon the post-exercise response seen at these temperatures.

Superimposition of the observed dry gas responses on the theoretical results demonstrates that the predicted and experimentally determined data are virtually identical from subfreezing through body temperature ranges (Figure 6). Comparison of the RHE-ΔFEV_1 relationship computed for this temperature range in the dry gas experiments with that from the previous studies shown in Figure 4 demonstrates that they, too, are identical (Figure 7). From 50°C onward, however, the actual responses in Figure 6 were somewhat greater than those expected. We believe that the explanation for the latter phenomenon is probably related to a loss of heat from the inspired air to the mucosa of the mouth and pharynx before reaching the

intrathoracic airways. There are two interrelated factors that would influence the magnitude and rate of this transfer. The first is the geometries of the conduits that are involved and the second is the duration of breathing the gas.

With respect to geometric considerations one can think of the supra and infra glottic airways as two heat exchangers in series. In the supraglottic airways airflow is quite turbulent, the surface area is large relative to that of the trachea and major bronchi, and the greatest thermal gradients between air and mucosa exist. All of these factors would favor contact with the gas and mucosa and would facilitate loss of heat from the air (14-17). With the passage of time, however, the initial thermal gradients would be expected to decrease as the mucosal temperature rose and some new equilibrium should be reached. We do not believe that this occurred because expired temperature did not change over the exercise period. One would have expected this to have happened if the mucosa of the supraglottic airways was acting as a heat sink for under these conditions as the mucosal temperature of the mouth and pharynx rose above core temperature, heat would have been transferred back from the mucosa to the relatively cooler expired air.

In any event decreasing RHE by adding a small amount of water to the hot air diminished the response according to predictions as shown in Figure 8. This demonstrates that if the heat loss from vaporization of water is minimized there can be a convective heat gain that serves to modify the response in accord with principles of RHE.

The present study demonstrates that within reasonable limits of inspired air conditions approximating climatic extremes the magnitude of the

post-exercise obstructive response in asthma is a positive function of the amount of respiratory heat transferred within the airways according to quantifiable predictions. Thus the post-exercise obstructive response relates directly to respiratory heat exchange.

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LEGENDS FOR FIGURES

Figure 1. The effect of exercise on pulmonary mechanics while breathing dry air at temperatures ranging from -11 to 80°C. The letters B and R below each graph represent baseline data and the response observed post-exercise, respectively. The data points are mean values, and the brackets indicate one standard error of the mean. The p values below each graph were derived from baseline-response comparisons. SGaw = specific conductance; FEV_1 = one second forced expiratory volume; RV = residual volume.

Figure 2. Comparison of the mean baseline-response differences for each variable for each inspired air temperature. The height of the bars are mean values, and the brackets represent one standard error of the mean. SGaw = specific conductance; FEV_1 = one second forced expiratory volume; RV = residual volume

Figure 3. The effect of exercise on pulmonary mechanics while breathing air at 50°C that is dry (solid circles) versus that containing 15.8 mg H_2O/L (open circles). The data points are mean values, and the brackets are one standard error of the mean. The letters B and R below each graph represent baseline data and the response observed post-exercise, respectively. The first 2 p values below each were derived from baseline response comparisons and the third from a comparison of the dry and wet data. SGaw = specific conductance; FEV_1 = one second forced expiratory volume; RV = residual volume.

Figure 4. The relationship between respiratory heat exchange (RHE) during exercise and the post-exertional percentage change in one second forced expiratory volume (% Δ FEV_1). These data were computed from references 1 and 3.

Figure 5. The maximal and minimal post-exercise responses possible at the extremes of humidity over temperature ranges from -11° to 110°C. The solid lines and circles represent the mean responses ± one standard error of the mean observed while breathing fully saturated air at various temperatures in previous studies from this laboratory (1,3). The broken curve is the predicted response for dry gas for the same exercise task. Equations 1 and 2 are the formulations for respiratory heat exchange (RHE) and the regression equation used to calculate the percentage change in one second forced expiratory volume (% Δ FEV_1) from RHE. Ti = inspired air temperature.

Figure 6. Actual data for maximal and minimal post-exercise responses At the extremes of humidity. The solid circles are the data from previous studies (1,3), while the solid squares represent the dry gas investigations in the present work. The data points are mean values, and the brackets indicate one standard error. The curve with the open circles and broken line represents the predicted dry gas response.

Figure 7. Comparison of the relationship between respiratory heat exchange (RHE) and percentage change in one second forced expiratory volumes (% Δ FEV_1) for our previous studies

(1,3) and for temperature ranges of -11° to 37°C in the present work.

Figure 8. Comparison of individual observed and predicted percentage changes in one second forced expiratory volumes (% Δ FEV_1), while breathing air at 50°C. with 15.8 mg H_2O/L during exercise. The solid line is the line of identity.

TABLE 1

Minute Ventilation and Inspired and Expired Air Temperatures During the Dry Gas Experiments

Subject	-10°C			25°C			37°C			50°C			65°C			80°C		
	$\dot{V}_E$	T_i	T_e	$\dot{V}_E$	T_i	T_e	$\dot{V}_E$	T_i	T_e	$\dot{V}_E$	T_i	T_e	$\dot{V}$	T_i	T_e	$\dot{V}_E$	T_i	T_e
1	74.5	-10	29	81.5	24	32	83.6	38	34	68.6	51	33	73.1	64	34	79.4	78	35
2	75.5	-12	29	84.6	24	33	70.6	38	33	87.3	48	33	73.0	65	34	75.0	79	35
3	68.9	-10	28	71.6	24	32	55.9	38	33	61.9	51	33	60.5	66	34	61.8	82	37
4	57.0	-12	28	61.3	26	32	54.1	37	33	59.2	51	32	56.6	66	34	58.8	79	36
5	78.3	-14	28	84.9	25	33	64.0	39	34	62.2	48	34	60.1	64	34	78.7	80	38
6	54.0	-10	25	62.8	25	32	63.0	37	33	58.0	50	33	56.0	65	35	51.5	78	39
7	72.5	-10	28	68.3	25	32	67.8	37	35	71.5	50	36	65.0	66	38	67.7	80	37
8	80.8	-11	25	89.9	25	32	83.2	37	34	83.0	52	36	85.7	65	40	79.6	79	40
MEAN	70.2	-10.9	27.5	75.6	24.8	32.3	67.8	37.6	33.6	69.0	50.1	33.8	66.3	65.1	35.4	69.1	79.4	37.1
SD	9.8	1.5	1.6	11.0	0.7	0.5	11.1	0.7	0.7	11.0	1.5	1.5	10.3	0.8	2.3	10.8	1.3	1.8

$\dot{V}_E$ = minute ventilation, L/min (BTPS); T_i = inspired air temperature, °C; T_e=expired air temperature, °C

TABLE 2

Minute Ventilation, Inspired and Expired Air Temperatures, and Water Contents While Breathing Partially Saturated and Dry Air at 50°C

	50°C Dry				50°C partially saturated			
Subject	$\dot{V}_E$	T_i	T_e	W_i	$\dot{V}_E$	T_i	T_e	W_i
1	64.5	49.0	35.5	0	65.5	49.5	37.0	11.1
2	66.2	50.0	33.0	0	70.0	52.0	35.0	13.0
3	55.1	50.5	35.0	0	60.3	50.5	36.0	13.4
4	44.3	51.0	35.0	0	42.7	51.0	36.0	15.2
5	57.6	52.0	36.0	0	54.0	52.0	38.0	22.0
6	57.0	48.0	32.5	0	54.3	49.0	35.0	14.9
7	67.9	50.0	36.0	0	67.3	50.0	37.5	14.6
8	77.8	52.0	35.0	0	84.9	50.0	37.5	22.0
MEAN	61.3	50.3	34.7	0	62.4	50.5	36.6	15.8
SD	10.1	1.4	1.4		12.7	1.1	1.2	4.0

$\dot{V}_E$=minute ventilation in L/min (BTPS); T_i=inspired air temperature in °C; T_e=expired air temperature in °C; W_i=inspired water content in mg H_2O/L air

TABLE A_1

EFFECTS OF EXERCISE ON PULMONARY MECHANICS WHILE BREATHING DRY AIR AT -10.9°C

Subject	SGaw		FEV_1		RV	
	B	R	B	R	B	R
1	0.13	0.03	2.87	1.04	1.25	3.05
2	0.14	0.05	3.11	1.40	1.47	4.25
3	0.16	0.05	2.47	1.16	1.21	2.64
4	0.08	0.04	1.65	1.11	1.22	2.53
5	0.11	0.03	2.73	1.50	1.78	4.45
6	0.09	0.02	2.25	1.02	2.49	4.10
7	0.13	0.04	2.91	1.68	1.27	2.79
8	0.11	0.04	3.45	2.03	3.11	5.08
MEAN	0.12	0.04	2.68	1.37	1.73	3.61
SD	0.03	0.01	0.56	0.36	0.71	0.97

SGaw=specific conductance in L/sec/cm H_2O/L; FEV_1=one second forced expiratory volume in L; RV=residual volume in L; B=baseline; R=post=exercise response

TABLE A_2

EFFECTS OF EXERCISE ON PULMONARY MECHANICS WHILE BREATHING DRY AIR at 24.8°C

	SGaw		FEV_1		RV	
Subject	B	R	B	R	B	R
1	0.14	0.05	2.96	1.33	1.12	2.81
2	0.13	0.07	3.47	1.99	1.38	3.95
3	0.15	0.06	2.46	1.88	1.33	1.52
4	0.09	0.06	1.68	1.44	1.45	2.14
5	0.10	0.04	2.84	1.59	1.85	3.23
6	0.13	0.04	1.74	1.18	1.67	3.77
7	0.11	0.05	2.95	1.79	1.43	2.47
8	0.12	0.06	3.79	2.32	3.36	4.92
MEAN	0.12	0.05	2.74	1.69	1.70	3.10
SD	0.02	0.01	0.75	0.38	0.71	1.10

SGaw=specific conductance in L/sec/cm H_2O/L; FEV_1=one second forced expiratory volume in L; RV=residual volume in L. B=baseline; R=post-exercise response

TABLE A_3

EFFECTS OF EXERCISE ON PULMONARY MECHANICS WHILE BREATHING DRY AIR OF 37.8°C

	SGaw		FEV_1		RV	
Subject	B	R	B	R	B	R
1	0.13	0.05	2.97	1.51	1.49	3.18
2	0.13	0.07	3.01	1.99	1.79	3.65
3	0.14	0.04	2.45	2.25	1.54	1.96
4	0.10	0.07	2.14	1.75	1.13	1.99
5	0.10	0.04	2.83	1.72	1.76	3.31
6	0.14	0.04	2.37	1.16	1.89	3.72
7	0.12	0.07	2.88	2.24	1.59	2.43
8	0.11	0.06	3.93	2.80	3.60	4.83
MEAN	0.12	0.06	2.82	1.93	1.85	3.13
SD	0.02	0.01	0.55	0.51	0.75	0.98

SGaw=specific conductance in L/sec/cm H_2O/L; FEV_1=one second forced expiratory volume in L; RV=residual volume in L. B=baseline; R=post-exercise response

TABLE A_4

EFFECTS OF EXERCISE ON PULMONARY MECHANICS WHILE BREATHING DRY AIR AT 50.1°C

	SGaw		FEV_1		RV	
Subject	B	R	B	R	B	R
1	0.12	0.05	2.91	1.56	1.13	3.09
2	0.13	0.07	3.34	2.20	1.57	2.94
3	0.13	0.07	2.29	1.42	1.14	1.84
4	0.08	0.05	1.26	1.00	2.05	2.68
5	0.10	0.03	2.88	1.67	1.83	3.44
6	0.12	0.04	2.05	1.15	2.02	3.39
7	0.10	0.05	2.95	2.05	1.72	2.27
8	0.12	0.06	3.76	2.65	3.38	4.08
MEAN	0.11	0.05	2.68	1.71	1.86	2.97
SD	0.02	0.01	0.79	0.56	0.71	0.71

SGaw=specific conductance in L/sec/cm H_2O/L; FEV_1=one second forced expiratory volume in L; RV=residual volume in L. B=baseline; R=post-exercise response

TABLE A_5

EFFECTS OF EXERCISE ON PULMONARY MECHANICS WHILE BREATHING DRY AIR AT 65.1°C

	SGaw		FEV_1		RV	
Subject	B	R	B	R	B	R
1	0.13	0.04	3.07	2.14	1.36	2.86
2	0.10	0.05	2.65	1.53	2.53	4.40
3	0.13	0.06	2.45	1.74	1.39	1.91
4	0.11	0.07	2.28	1.80	1.38	1.74
5	0.09	0.03	2.84	1.52	1.84	2.94
6	0.12	0.04	2.27	1.43	2.17	3.15
7	0.11	0.06	2.84	2.56	1.64	2.20
8	0.11	0.05	3.67	2.76	3.22	4.42
MEAN	0.11	0.05	2.76	1.94	1.94	2.95
SD	0.01	0.01	0.47	0.50	0.66	1.03

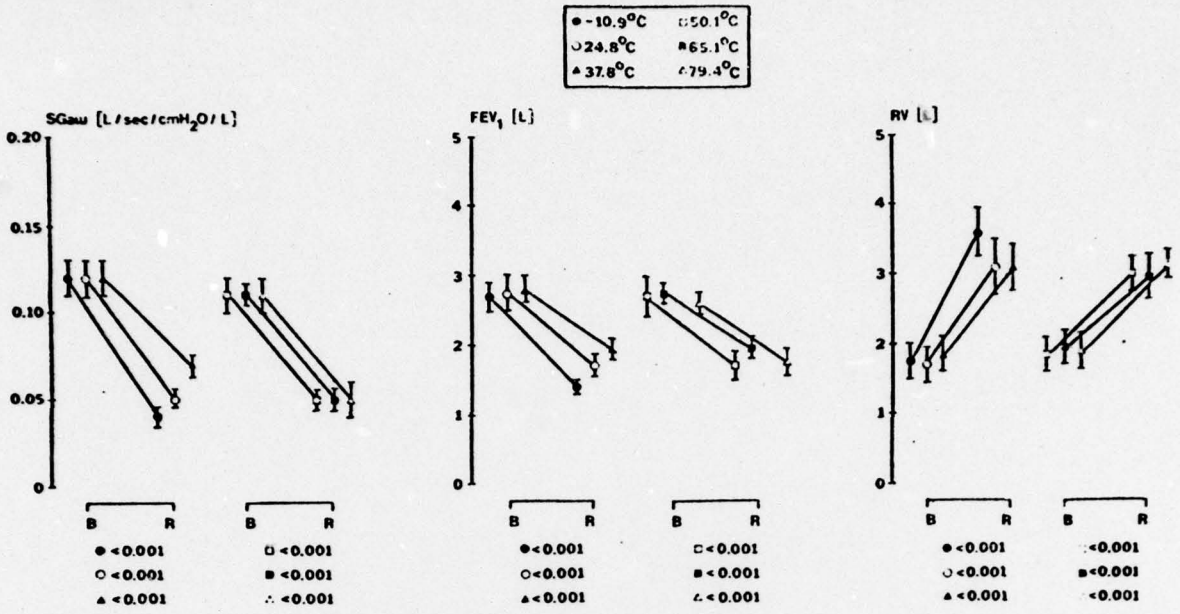
SGaw=specific conductance in L/sec/cm H_2O/L; FEV_1=one second forced expiratory volume in L; RV=residual volume in L. B-baseline; R=post-exercise response

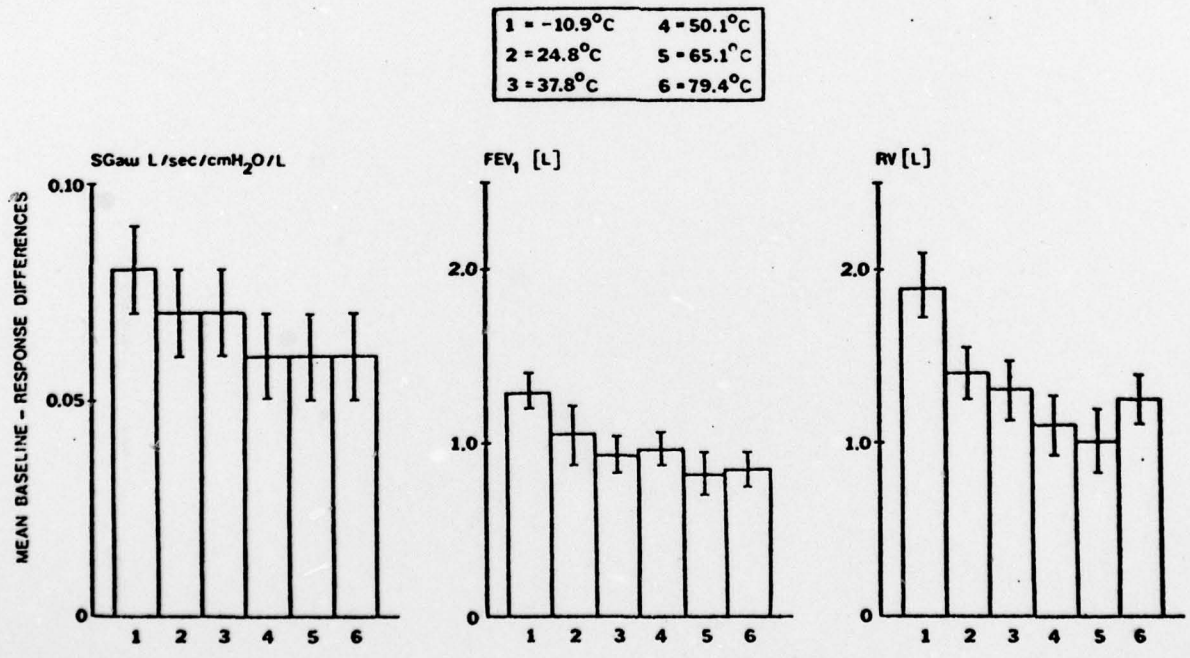
TABLE A_6

EFFECTS OF EXERCISE ON PULMONARY MECHANICS WHILE BREATHING DRY AIR AT 79.4°C

	SGaw		FEV_1		RV	
Subject	B	R	B	R	B	R
1	0.12	0.04	2.50	1.35	1.57	3.30
2	0.12	0.07	2.81	1.99	2.22	3.43
3	0.15	0.07	2.81	1.99	1.51	1.89
4	0.09	0.03	1.86	1.23	1.32	2.90
5	0.10	0.04	2.61	1.44	1.76	3.18
6	0.13	0.04	2.40	1.28	1.97	3.79
7	0.10	0.05	2.50	1.82	1.41	2.97
8	0.10	0.07	3.23	2.91	3.41	3.76
MEAN	0.11	0.05	2.59	1.75	1.90	3.15
SD	0.02	0.02	0.39	0.56	0.68	0.61

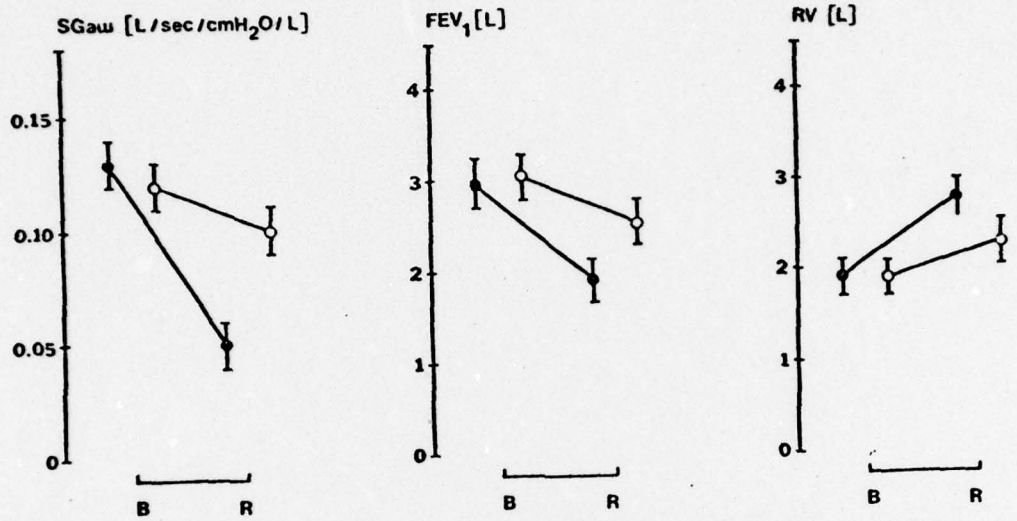
SGaw=specific conductance in L/sec/cm H_2O/L; FEV_1=one second forced expiratory volume in L; RV=residual volume in L. B=baseline; R=post-exercise response


● -10.9°C
○ 24.8°C
▲ 37.8°C
□ 50.1°C
■ 65.1°C
△ 79.4°C
SGaw [L/sec/cmH2O/L]
FEV1 [L]
RV [L]
B
R
● <0.001
○ <0.001
▲ <0.001
□ <0.001
■ <0.001
△ <0.001

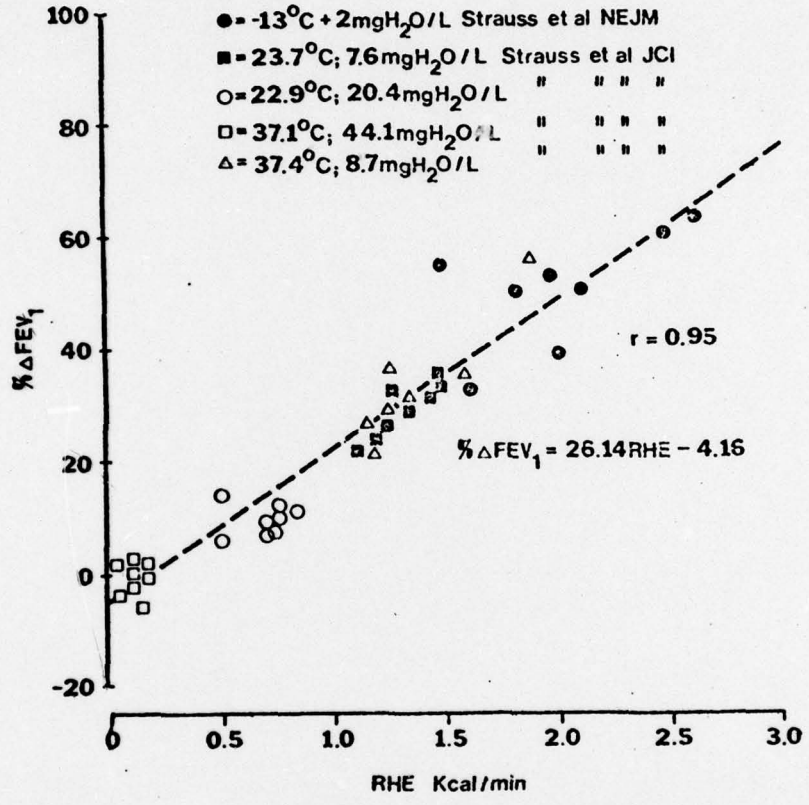

1 = -10.9°C
2 = 24.8°C
3 = 37.8°C
4 = 50.1°C
5 = 65.1°C
6 = 79.4°C
SGaw L/sec/cmH2O/L
FEV1 [L]
RV [L]
MEAN BASELINE - RESPONSE DIFFERENCES

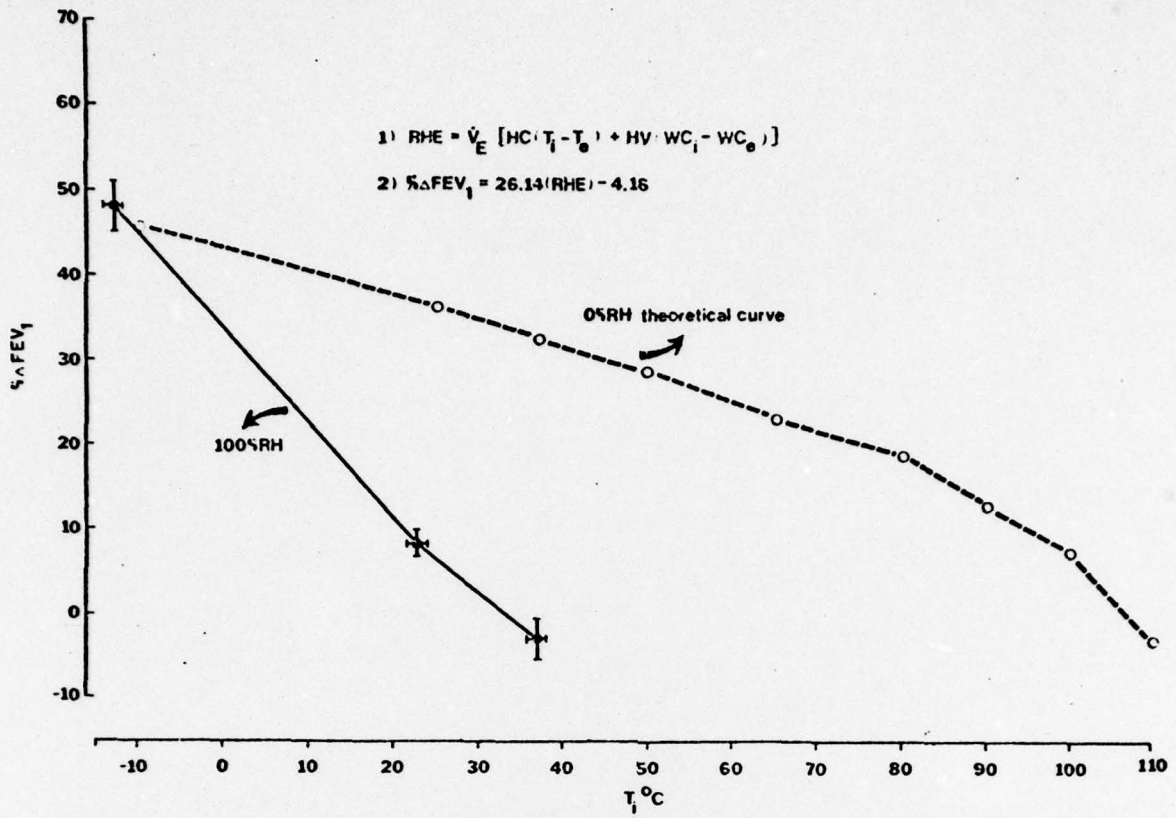
● 50°C, 0mgH_2O / L

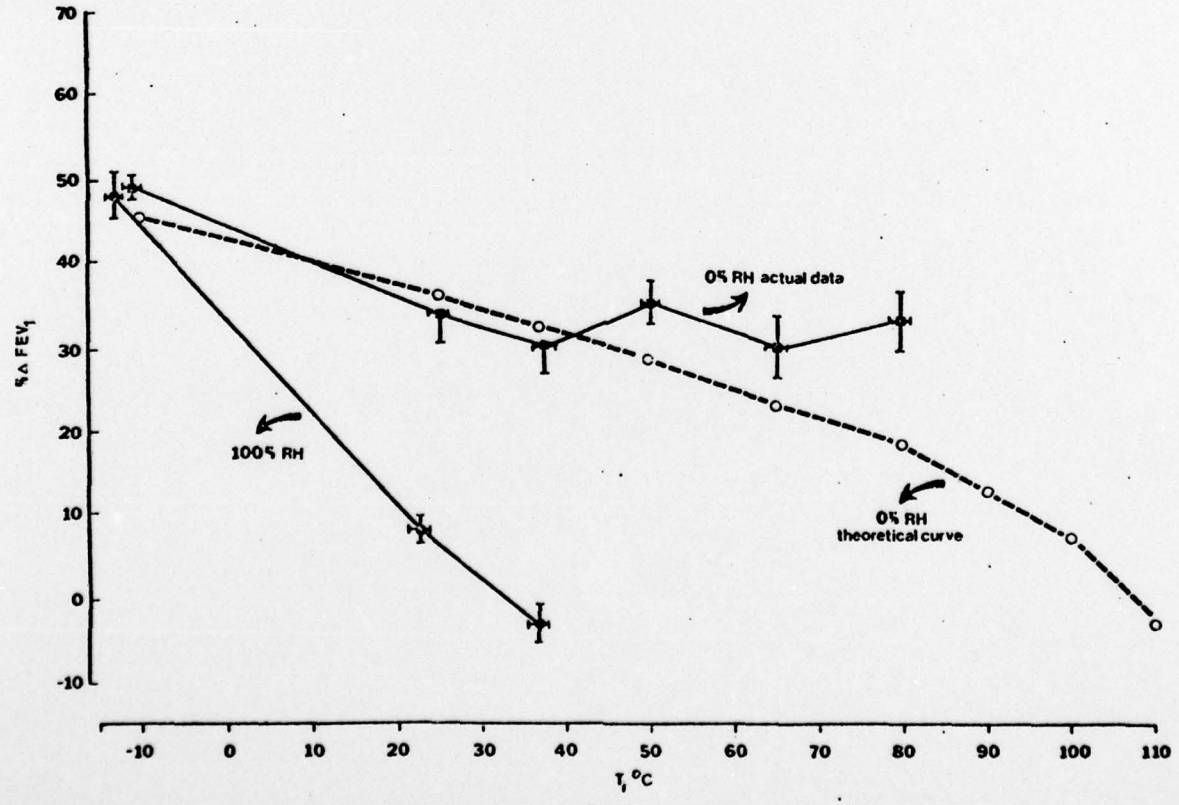
○ 50°C, 15.8mgH_2O / L

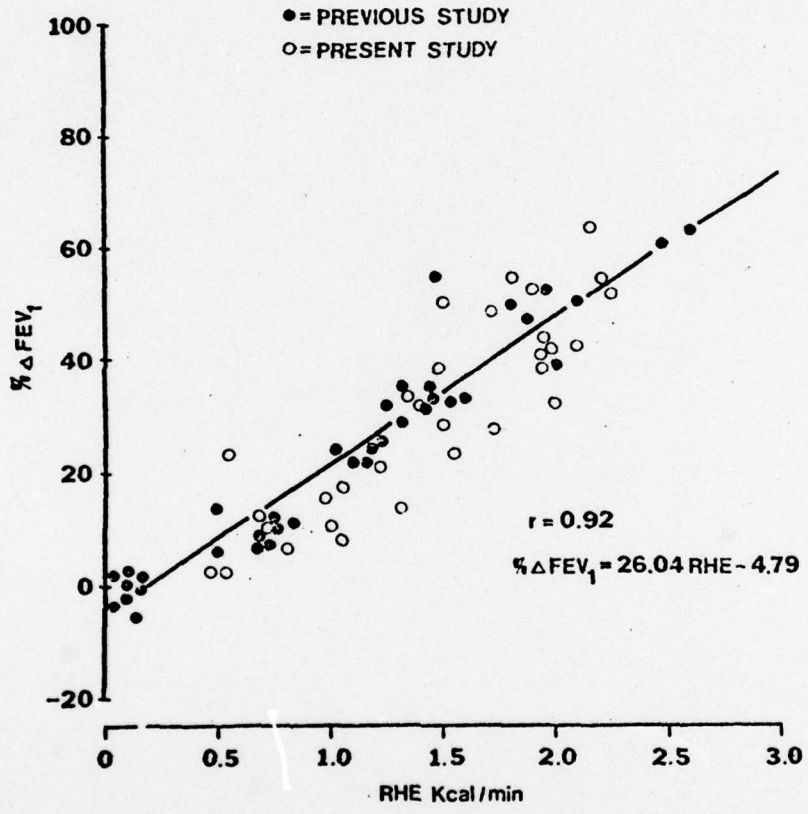


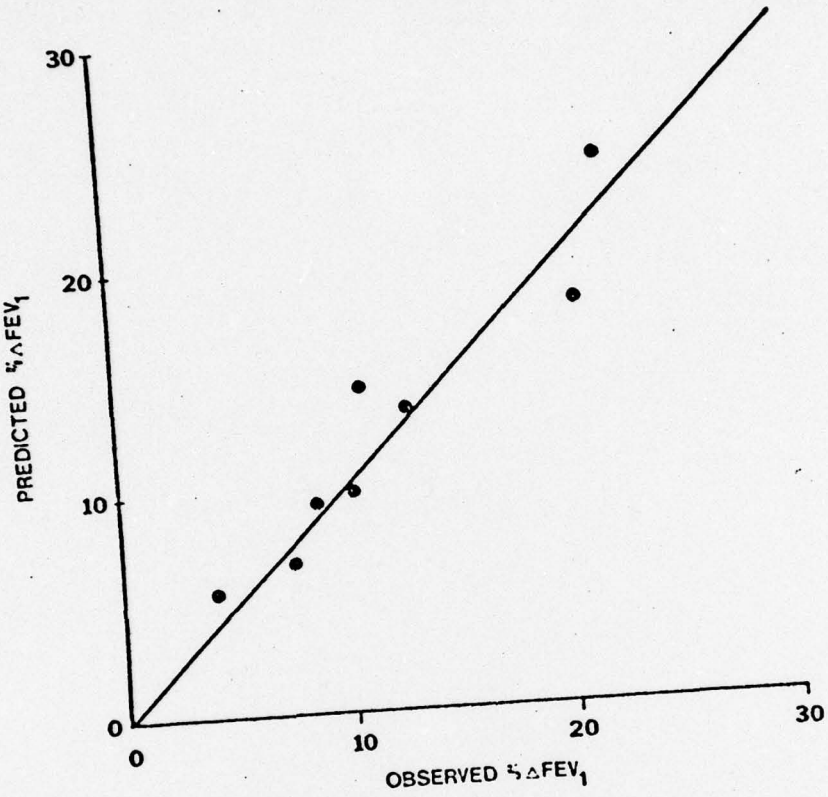
	SGaw	FEV_1	RV
50°C, 0mgH_2O	<0.001	<0.001	<0.001
50°C, 15.8mgH_2O	<0.005	<0.025	<0.02
DRY VS WET	<0.001	<0.001	0.02


●= -13°C + 2mgH2O/L Strauss et al NEJM
■= 23.7°C; 7.6mgH2O/L Strauss et al JCI
○= 22.9°C; 20.4mgH2O/L " " " "
□= 37.1°C; 44.1mgH2O/L " " " "
△= 37.4°C; 8.7mgH2O/L
r = 0.95
%ΔFEV1 = 26.14RHE − 4.16
%ΔFEV1
RHE Kcal/min
100
80
60
40
20
0
-20
0
0.5
1.0
1.5
2.0
2.5
3.0


1) RHE = $\dot{V}_E$ [HC ($T_i - T_e$) + HV ($WC_i - WC_e$)]
2) $\%\Delta FEV_1$ = 26.14 (RHE) - 4.16
0%RH theoretical curve
100%RH
$\%\Delta FEV_1$
T_i °C


0% RH actual data
100% RH
0% RH
theoretical curve
$\%\Delta FEV_1$
T_i °C


●= PREVIOUS STUDY
○= PRESENT STUDY
100
80
60
40
20
0
-20
% Δ FEV1
0
0.5
1.0
1.5
2.0
2.5
3.0
RHE Kcal/min
r = 0.92
% Δ FEV1 = 26.04 RHE - 4.79


30
20
10
0
0
10
20
30
PREDICTED % ΔFEV1
OBSERVED % ΔFEV1

Unclassified

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20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

By having our subjects inhale dry air at various temperatures ranging from subzero to 80°C in a random fashion, we have tested the hypothesis that it is the total heat flux in the tracheobronchial tree during exercise that determines the degree of post-exertional obstruction that develops in asthma. Our purpose in this was to determine if heat could be transferred from the air to the mucosa so as to offset evaporative losses from the airways. The observed post-exercise responses were then compared to those that we predicted would occur

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based upon the relationship of respiratory heat exchange and exercise response determined from previous studies in this laboratory employing fully saturated air. The observed responses breathing completely dry air fell as the temperature was increased and exactly matched theoretical predictions over a range of inspired air temperatures from -11 to 37 °C. Above 37 °C the observed response exceeded predictions, indicating that it was not possible to provide sufficient heat per se in the air to offset the vaporization of water. However, when small amounts of water were added to the inspirate at high temperatures, bronchospasm was virtually abolished and the response again closely matched theoretical expectations. We conclude that the magnitude of exercise induced asthma is directly proportional to the thermal load placed upon the airways and that this reaction is quantifiable in terms of respiratory heat exchange.